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MACHO RR Lyrae in the Inner Halo and Bulge

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Abstract. The RR Lyrae in the bulge have been proposed to be the oldest populations in the Milky Way, tracers of how the galaxy formed. We study here the distribution of ~ 1600 bulge RR Lyrae stars found by the MACHO Project. The RR Lyrae with $0.4 < R < 3$ kpc show a density law that is well fit by the extension of the metal-poor stellar halo present in the outer regions of the Milky Way.

1. The Oldest Populations in the Galaxy?

The importance of the Milky Way halo in terms of galaxy formation theories was recognized very early on (Eggen et al. 1962): the halo is the oldest component, and its stars could have formed before the Galaxy had fully collapsed. Alternatively, if the Milky Way evolved through merging and the accretion of smaller satellites (as predicted by the cold dark matter clustering model), the halo would represent the disrupted stellar component of the original small galaxies (Searle & Zinn 1978). In both of these scenarios, however, the oldest stars will be the metal-poor stars located deep in the potential well, in the inner bulge (Lee 1992, van den Bergh 1993, Ortolani, et al. 1995, Minniti 1996). The remains of an ancient population of globular clusters destroyed by dynamical processes (which are enhanced in the bulge region) would also be found deep in the potential well.

It is very difficult to select these old metal-poor stars in the inner bulge, because of contamination from the other Milky Way components, namely disk and bulge. The field population across the bulge is predominantly metal-rich: from spectroscopy of 400 K giants with $R < 2$ kpc, Minniti et al. (1995) concluded that the metal-poor component in this region is only a small fraction of the total number of stars. Fortunately, the microlensing surveys such as MACHO have produced a wealth of stellar photometry in the most crowded parts of the Milky Way bulge. In particular, they find very large numbers of RR Lyrae variable stars in the bulge fields (Alcock et al. 1998). These inner RR Lyrae stars are

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old and metal-poor (Walker & Terndrup 1991), and may be excellent tracers of the oldest stellar populations in the Milky Way.

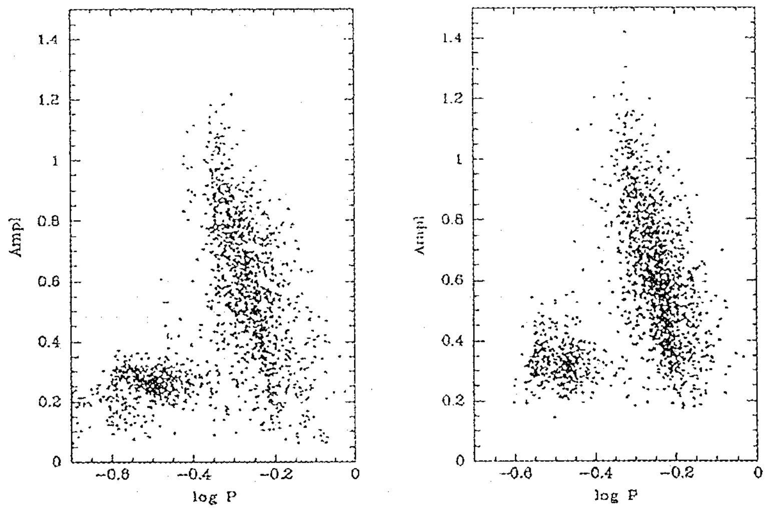

Figure 1. Period-amplitude diagram for bulge (left) and LMC (right) RR Lyrae stars from the MACHO database.

We have selected 1150 RR Lyrae type ab (fundamental pulsators) and 450 RR Lyrae type c (first overtone pulsators) from the MACHO bulge database (Minniti et al. 1997, Alcock et al. 1998). These RR Lyrae have extensive V and R photometry, from which we can make light curves, and measure accurate periods and amplitudes.

The Bailey or period-amplitude diagram of bulge and LMC RR Lyrae in the MACHO database is shown in Figure 1 (see also Minniti et al. 1997). Metallicity is one of the major parameters that drive the appearance of this diagram (see Bono et al. 1997a, b). In particular, the bulge RR Lyrae are more metal-rich, with mean $[Fe/H] = -1.0$ (Walker & Terndrup 1991), than the LMC RR Lyrae, with mean $[Fe/H] = -1.6$ (Alcock et al. 1996). Note also that the bulge RR Lyrae types ab and c have shorter mean periods than their LMC counterparts, and that the amplitudes of bulge RRc stars are smaller in the mean than the LMC ones, in agreement with theoretical pulsation predictions for different metallicities (Bono et al. 1997a, b). These facts indicate that the inner halo contains an extreme Oosterhoff I population, in contrast with the metal-poor globular clusters and outer halo, which are dominated by an Oosterhoff II population. This is not surprising, given the gradient observed in the field RR Lyrae: they have higher metallicity with decreasing radial distance from the Galactic center (Suntzeff et al. 1991).

2. Spatial Distribution of RR Lyrae with $R < 3$ kpc

The old and metal-poor stellar halo follows a steep power density law (e.g. Saha 1985, Preston et al. 1991, Layden 1997). The present work allows us to extend this distribution into the inner bulge regions.

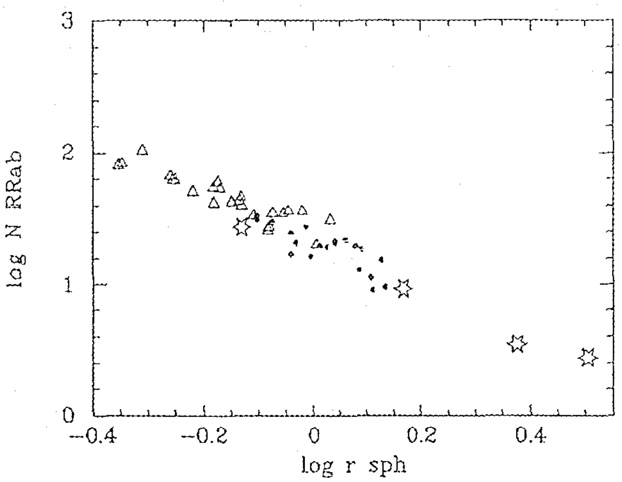

Figure 2. Surface density distribution of RR Lyrae in the bulge as function of log r (where r is the projected distance from the Galactic center in kpc). The triangles are from MACHO, the full circles are from Alard (1996), and the stars are from Wesselink (1987).

Figure 2 shows radial distribution of the number counts of RR Lyrae in the bulge fields after discarding background RR Lyrae that belong to the Sgr dwarf (Alard 1996, Alcock et al. 1997). This distribution yields a power density law of the form $\rho \propto r^{-3.0}$. Even though there is a metallicity gradient with Galactocentric distance, with the inner RR Lyrae being more metal-rich than the outer ones (Suntzeff et al. 1991, Walker & Terndrup 1991), the inner RR Lyrae with $R < 3$ kpc follow the extrapolation of the halo power density law into the inner regions. There is no apparent turn-over of this distribution, even in the innermost fields, indicating that the RR Lyrae are very concentrated, with core radius $R_c < 0.5$ kpc. We also determine that the RR Lyrae surface distribution is flattened, with $b/a = 0.7$, consistent with Preston et al. (1991).

The distribution is very concentrated: Figure 2 shows that we expect ~10 times more RR Lyrae in the inner bulge fields than in the outer ones. We have corrected for incompleteness (estimated to be 10% in a typical bulge field such as Baade's window) using external comparisons (Alcock et al. 1996, 1998), and also counts of contact binary stars. In general, the inner fields are the most reddened and crowded ones, where completeness is more severe. However, if we overestimated the completeness in the inner regions, the distribution shown in Figure 2 would be even steeper.

Note that the inner RR Lyrae, although more metal-rich than the outer halo ones, are still more metal-poor than the bulge population. It is the metal-rich bulge population that dominates the underlying mass and also the integrated light (e.g. in the fields studied, there is one RR Lyrae for every 550 clump giants).

3. Implications for the Bulge Microlensing Events

The bulge fields contain a mixed stellar population. Figure 3 shows how the inner halo RR Lyrae distribution compares with the distribution of other tracers. We show the counts of clump giants, which are metal-rich tracers of the bulge, contact binaries, which are tracers of the disk, and candidate microlensing events found by the MACHO Project.

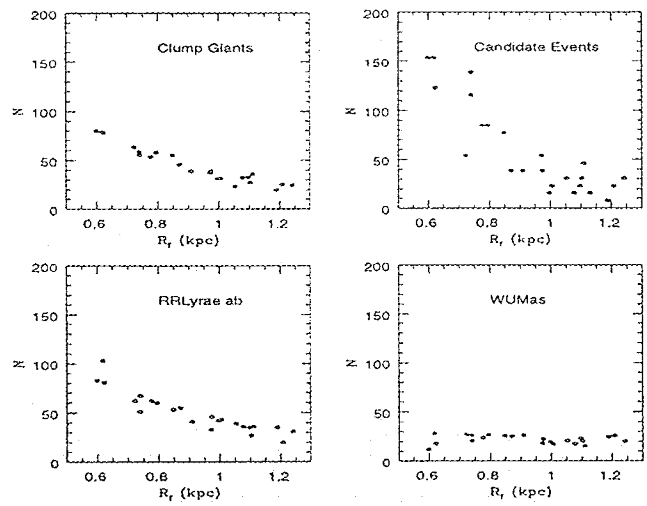

Figure 3. Number counts –arbitrarily normalized– of different tracers as function of projected distance from the Galactic center (for $R_o = 8$ kpc, $b/a = 0.7$). The bulge tracers (clump giants), and the inner halo tracers (RR Lyrae) are very concentrated, while the disk tracers (W UMa stars) show a flat distribution. The candidate microlensing events are more concentrated than any of the known stellar populations.

Are the candidate microlensing events being alerted by MACHO really microlensing, or just a new kind of variable star? For example, some of the bursts of cataclysmic variables can be fitted nicely by a microlensing light curve, and this can lead to misidentifications (e.g. Della Valle 1994). Indeed, a few alerts were later found to have repeated outbursts. However, it has been demonstrated in specific cases, and it is generally accepted that we are detecting real microlensing events towards the bulge. The distribution shown in Figure 3 provides another confirmation of this fact.

Since the bulge, disk, and halo components have different kinematics in these inner fields (Minniti 1996), microlensing events in these components would have different distributions of observed parameters. These candidate events are more concentrated than any other known stellar population that trace the bulge (clump giants), disk (W UMa stars), and halo (RR Lyrae). This is consistent with the microlensing interpretation, ruling out any kind of variable star.

While the real number of microlensing events may increase (see e.g. Drake et al. these proceedings), it is clear that these candidates are much more concentrated than any other known stellar population. This comparison is fair if we assume that: 1. to first order our photometric completeness limits are similar for variable stars and microlensing. 2. to first order the window function for detecting variable stars and microlensing is similar. Clearly, this is only a first approximation, and more work is needed to refine the radial dependences of microlensing. This work includes an efficiency calculation for microlensing and variable stars as function of several parameters (reddening, crowding, magnitude, color, seeing, etc.), indeed a daunting task for the future!

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